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Effect of Sediment Load on the Rating Curves of 0.6-Foot HS Flumes

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Standard HS flumes are widely used for measuring flow in drainage and erosion research. The calibration of these flumes is based on a stable relationship between depth of flow and rate of flow. The accuracy of depth of flow as a measure of the rate of flow increases as the point of measurement approaches the point of critical flow. However, only in the subcritical flow region, where the velocity head is negligible and changes in depth are approximately equal to changes in specific energy, is depth of flow a good measure of rate of flow. Thus, the HS flume is designed to measure flows with considerable accuracy by placing the point of depth measurement in the subcritical flow region and as near as possible the point where flow changes to critical depth and velocity. The flume floor must be installed almost level to provide subcritical flow at and above the point of measurement.

The rating curves for HS flumes are based on clear water flow and design floor conditions.[3] In actual operation, however, particularly in erosion research, the water flow to be measured usually contains some sand and finer soil particles. Sediment, both in the measured water and that deposited on the floor of the flume, can affect the hydraulic characteristics and accuracy of the flume.

TEST PROCEDURE

A series of tests were made to determine the effect of different amounts of sand and soil load in the measured water on the rating curves of 0.6-foot HS flumes and also to determine why the rating curves were affected. The corrections determined by these tests can be used to make more accurate flow measurements of sediment-laden water.

The tests were conducted at an outdoor lakeshore site near Morris, Minn. Water was supplied by centrifugal pump from the lake to a constant-head supply tank set on a 10-foot-high tower. The water was then conducted through one of three pipes, each equipped with a different sized orifice meter, to a $2\frac{1}{2}$-foot-wide by 5-foot-long tank equipped with baffles and on one end of which was mounted a short supply channel. A 2- by 5-inch hole in the floor of the supply channel at the lower end allowed the flow to fall straight down into the upper end of the approach section of the flume to be rated. Rate of water inflow to the test flume was measured from the supply pipe best suited for the flow desired. Before the tests began, the orifice meters were calibrated with a weighing tank set below the test flume (fig. 1).

A Gandy Model 901 granular applicator[4], powered by an electric motor, calibrated for both sand and soil was used to supply sand and soil loads to the measured water in the supply channel. The weighing tank below the flume was used for measuring low flows.

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[1] Contribution from the Corn Belt Branch of the Soil and Water Conservation Research Division, Agricultural Research Service, USDA, in cooperation with the Minnesota Agricultural Experiment Station.

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[3] Holton, H. N., Minshall, N.E., and Harrold, L. L. Field manual for research in agricultural hydrology. U.S. Dept. Agr., Agr. Handb. 224, 215 pp., illus. 1962.

[4] Trade names are used in this publication for the purpose of providing specific information. Mention of a trade name does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture over others not mentioned.

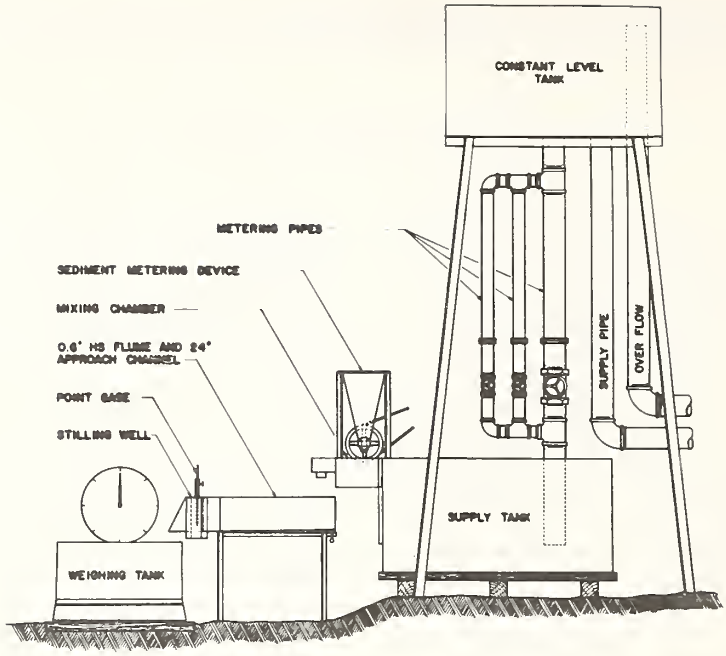

Figure 1.--Diagram of test setup.

A special flume made of 0.5-inch-thick plexiglass with size specifications for a 0.6-foot HS flume was used for the tests. The flume was constructed with a 24-inch-long approach channel and stilling well of the same material. The clear plastic construction permitted photographs to be made of the sediment load and deposition, and made measurement of the depth of deposition easier. Comparison tests were also made with a standard galvanized sheet metal flume and approach section. There were no significant differences in the calibration curves for the two test flumes using clear water.

Tests were made using first sand and then soil. The washed sharp mortar sand used had the following particle-size distribution:

Classification	Size, mm.	Percent
Very coarse	2.00-1.00	10.4
Coarse	1.00- .50	53.1
Medium	.50- .25	32.7
Fine	.25- .10	3.4
Very fine	.10- .05	.4

The soil used was Barnes topsoil from the Barnes-Aastad Research Farm. The mechanical composition of this sandy loam soil was 62, 19, and 19 percent sand, silt, and clay, respectively.

Both sand and soil were air dried and then sifted through a No. 10 screen (2.00 mm.) before using in the tests. The amount of sand or soil used as a percent by weight of water was 0, 1, 2, 4, 6, 8, and 12. Rates of flow used for the tests were 0.003, 0.006, 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.08, and 0.10 c.f.s. Tests were conducted for 10 minutes at each flow rate and sediment content for both sand and soil except for a few tests at high flow rates and high percentages of sediment when shorter times were used. Maximum flow rates were limited to 0.10 c.f.s. because of excessive splash losses at higher rates.

Although low flows with small percentages of soil took longer to stabilize than higher flows, it appeared that relatively stable sediment conditions had been reached in the flume at the end of each 10-minute period since in all cases considerably more sediment was added to the measured water during a test run than was retained in the flume at the end of the test run. However, there were continual small changes in the sediment pattern in the flume floor as long as flow continued. All tests were started with a clean flume.

In addition to the tests with sand and soil, a series of tests were conducted with a friction-reducing additive in clear water to study the effect of a lower friction or drag of the measured water on the flume rating. Tests were made with both 15 and 30 p.p.m. of polyethylene oxide, Union Carbide Polyox WSR 301, added to the measured water.

The measurements made during and following the tests were rate of flow, kind and amount of sediment, depth of water in stilling well, water temperature, and amount and location of sediment in flume at completion of tests. Photographs of sediments in the flume were taken at 3-, 5-, and 10-minute intervals after the start of each test. From these photographs, the depth of deposition and the effective gradient of the flume floor were measured.

RESULTS WITH SOIL

Soil in the measured water reduced the measured stage in the stilling well for all flow rates greater than 0.01 c.f.s. (table 1). Except for these low flow rates of 0.01 c.f.s. or less where results were erratic for a given flow rate, reduction in stage depth increased with increase in the percent soil in the measured water. The flow rate at which the maximum difference in stage depth between sediment-laden water and clear water varied with the percent silt load. The maximum difference with 6-, 8-, and 12-percent soil in the water occurred at a flow rate of 0.06 c.f.s. With 2-percent soil in the water, the maximum difference was with 0.03 c.f.s. flow rate; with 4-percent soil, the maximum difference was with 0.04 and 0.05 c.f.s. flow rates. These differences in measured stage represent errors up to 30 percent when estimating flow rates by using the standard calibration curves.

Table 1.--Change in stilling well stage of 0.6-foot HS flume resulting from different amounts of soil in the measured water

Flow rate c.f.s.	Amount of soil in water (percent)[1]					
	1	2	4	6	8	12
	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.
0.003	-0.008	-0.003	-0.014	-0.012	-0.014	-0.014
.006	+.001	+.001	-.004	+.004	-.006	-.001
.01	+.002	+.006	+.007	-.005	-.011	+.003
.02	-.001	-.004	-.005	-.004	-.012	-.010
.03	-.002	[2] -.016	-.028	-.029	-.029	-.032
.04	-.001	-.014	[2] -.030	-.034	-.030	-.033
.05	-.001	-.014	[2] -.030	-.031	-.031	-.033
.06	-.001	-.012	-.028	[2] -.040	[2] -.044	[2] -.047
.08	-.001	-.010	-.024	-.028	-.030	-.040
.10	-.002	-.009	-.012	-.014	-.019	-.034

[1] Minus sign indicates reduction in stage depth when soil added to measured water.

[2] Maximum reduction in stage for given amount of soil in measured water.

With a 1-percent sediment load, the amount of soil remaining in the flume and approach channel at the end of the test runs increased as the flow rate increased from 0.003 to 0.05 c.f.s. and remained about uniform for higher flows. With a 12-percent load, the amount of soil remaining in the flume and approach channel continually increased with flow rate (figs. 2-4). At the higher flow rates, the energy of the water falling into the approach kept the rear part of the channel relatively free of sediment. As a result, the larger accumulation of sediment was in the middle part of the approach channel.

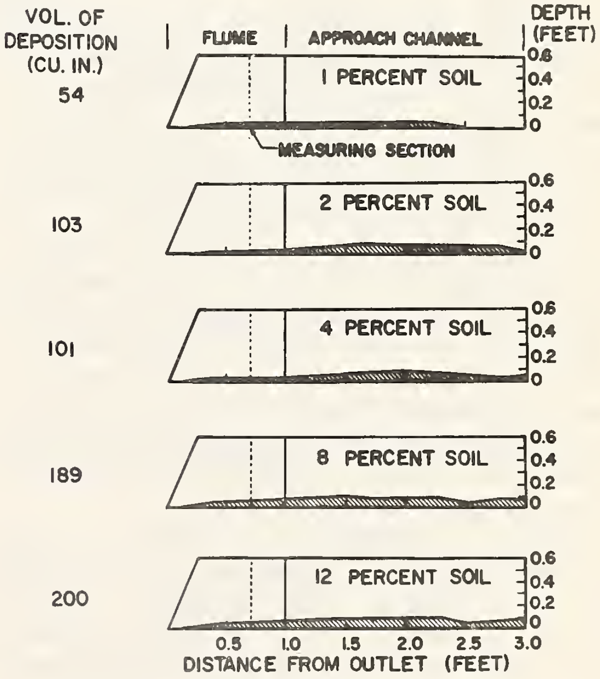

Figure 2.--Soil deposition in 0.6-foot HS flume, 0.01 c.f.s. flow rate.

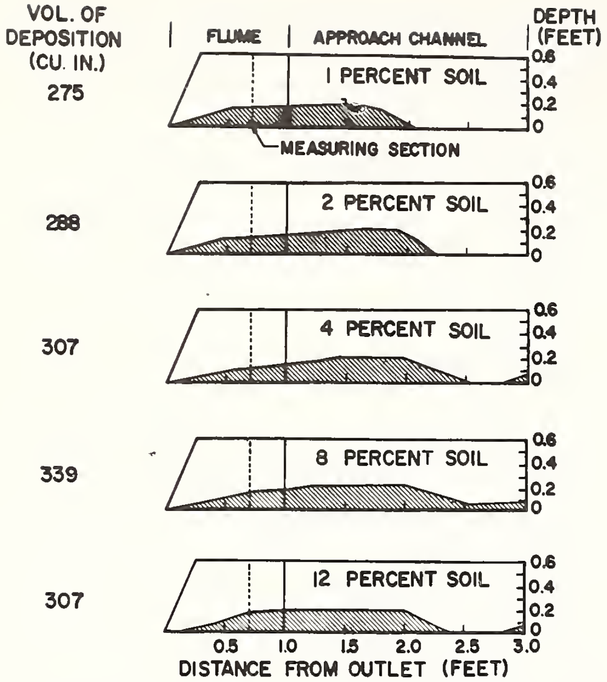

Figure 3.--Soil deposition in 0.6-foot HS flume, 0.04 c.f.s. flow rate.

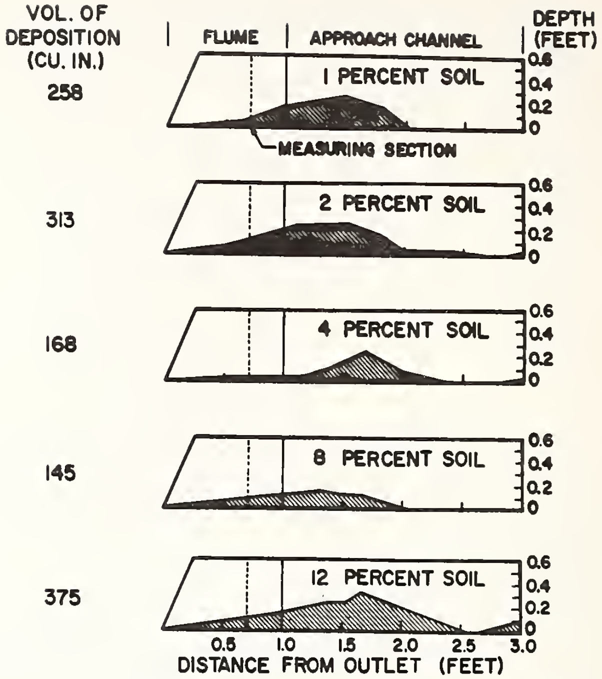

Figure 4.--Soil deposition in 0.6-foot HS flume, 0.10 c.f.s. flow rate.

RESULTS WITH SAND

Somewhat similar results were observed when sand was the test sediment rather than soil. The change in stage increased for all sand loads when the flow rate was increased from 0.02 to 0.10 c.f.s. (table 2). For flows of 0.01 c.f.s. and below, the results were erratic. For flow rates of 0.03 and 0.08 c.f.s., the greatest difference was measured with 4-percent sand in the water. For flow rate of 0.04 c.f.s., the greatest difference was measured with 2-percent sand; for 0.05 and 0.06 c.f.s., the greatest difference was with 1-percent sand. For flow rate of 0.10 c.f.s., the greatest difference in stage height was measured with 6-percent sand in the measured water (table 2).

Again as with soil, the differences in measured stage heights because of sand in the measured water represent errors up to 30 percent when standard calibration tables are used to estimate flow rate.

The amount of sand deposited in the flume and approach channel during a 10-minute run was affected by both flow rate and percentage of sand in the water (figs. 5, 6, 7). With flows of 0.02 c.f.s. and less, the deposition usually increased in depth from the outlet to the upper end of the approach cannel. At higher flow rates the turbulence of the falling water tended to keep the sand in suspension longer and deposition at the upper end of the approach channel was reduced. With a 2-percent sand load end a 0.10 c.f.s. flow rate, no deposition was noted in the upper 10 inches of the approach channel. With a 4-percent sand load and the same flow rate, there was a small area free of deposition near the upper end of the approach channel. With 12-percent sand in the water and the same flow rate of 0.10 c.f.s., the deposition was about a uniform 3 inches in depth in the upper 2 feet of the approach channel and then gradually reduced in depth to the outlet.

Table 2.--Change in stilling well stage of 0.6-foot HS flume resulting from different amounts of sand in the measured water

Flow rate c.f.s.	Amount of sand in water (percent)[1]					
	1	2	4	6	8	12
	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.
0.003	0.000	+0.004	-0.008	-0.007	-0.009	--
.006	-.007	-.009	-.011	-.006	-.009	+0.006
.01	+.001	+.001	+.001	-.005	-.004	+.006
.02	+.001	--	+.001	-.008	-.005	+.003
.03	.000	-.017	[2] -.019	-.017	-.007	-.005
.04	.010	[2] -.026	-.022	-.021	.018	.016
.05	[2] -.039	-.038	-.031	-.031	-.030	-.024
.06	--.047	-.042	-.039	-.038	-.034	-.030
.08	-.039	-.059	[2] -.061	-.053	-.051	-.040
.10	-.025	-.059	-.074	[2] -.076	-.057	-.044

[1] Minus sign indicates reduction in stage depth when soil added to measured water.

[2] Maximum reduction in stage for given amount of sand in measured water.

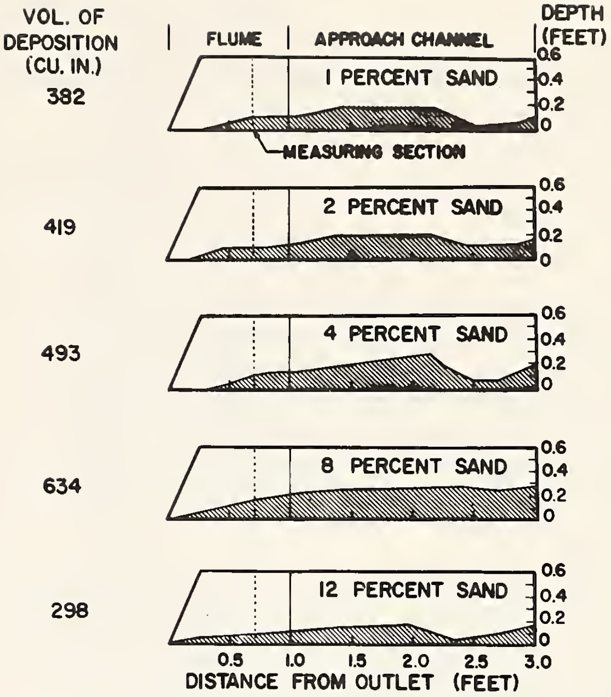

Figure 6.--Sand deposition in 0.6-foot HS flume, 0.04 c.f.s. flow rate.

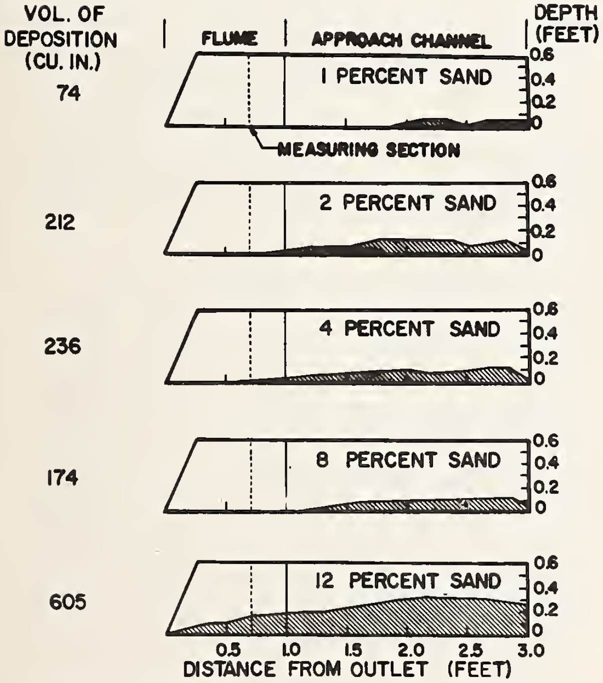

Figure 5.--Sand deposition in 0.6-foot HS flume, 0.01 c.f.s. flow rate.

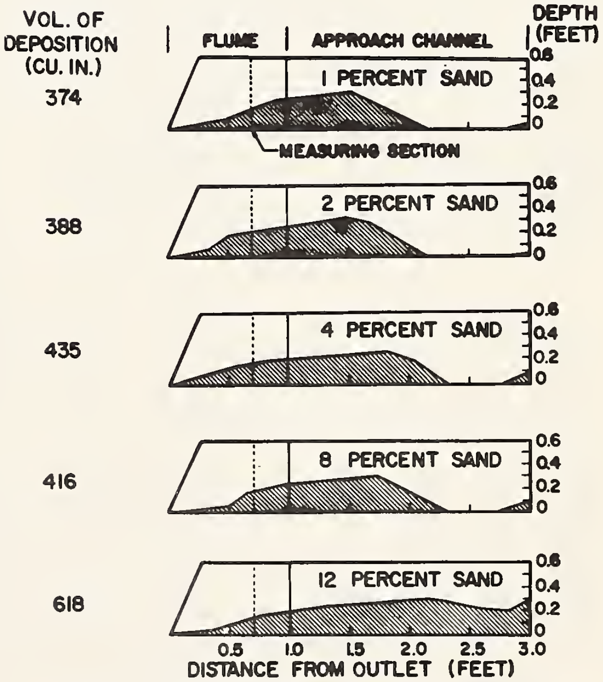

Figure 7.--Sand deposition in 0.6-foot HS flume, 0.10 c.f.s. flow rate.

RESULTS WITH POLYETHYLENE OXIDE

The friction-reducing additive had no effect on stage in the stilling well for all flow rates.

ANALYSIS OF RESULTS

Sediment deposited in the bottom of an HS flume acts as an artificial flume floor with a steeper grade than the original floor and with a higher elevation. This steeper grade may approach and sometimes may exceed the critical slope for the particular discharge passing through it, resulting in the water flow approaching both the critical depth and critical velocity before reaching the point of measurement.

When measuring clear water in a clean flume, the specific energy (E) will be the sum of the depth of flow (d) and the velocity head (H_v) and will equal the total energy (H). When there is sediment deposited on the floor of the flume, the total energy (H) will be the same sum plus an additional factor, the depth of the deposition (Z). For equivalent flow rates, the depth of flow of sediment-laden water plus the depth of deposited sediment is usually slightly less than the depth of flow of clear water, the difference being equal to the increased velocity head of the sediment-laden water.

When supercritical flow occurs, the velocity head accounts for a greater proportion of the specific energy of the flow and depth accounts for proportionally less. The stilling well attached to the flume measures stage and is little affected by the velocity head, so with supercritical flow past the measuring point, stilling well measurements reflect only part of the total energy gradient, or head, associated with a given discharge. Thus, large changes in rate of flow may result in only small changes in depth of flow, and the flow rate can no longer be accurately indicated by stage measurements in the stilling well.

Essentially all of the measurement errors obtained with soil- and sand-laden water were accounted for by changes in the flow characteristics in the flume channel caused by the deposition of sediment on the flume floor. Errors resulting from changes in the viscosity and density of the measured water because of the suspended sediment were negligible. Deposition of sediment on the floor of the flume and approach channel caused an increase in the slope of the floor. This increased slope produced an increased velocity of flow so that the depth of flow was reduced for a given flow rate. At the same time the stage was increased by the depth of the deposited sediment. This increase in stage caused by the depth of sediment was almost as great in most cases, and actually greater in a few cases, with low flows than the reduction in depth of flow

Table 3.--Hydraulic factors of an 0.6-foot HS flume with 0, 1, 4, and 12 percent soil by weight in measured water

Q c.f.s.	d_c [1]	V_c [2]	0 percent soil			1 percent soil				4 percent soil				12 percent soil			
			d	Hv	H[3]	Z	d	Hv	H[3]	Z	d	Hv	H[3]	Z	d	Hv	H[3]
	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.
0.003	0.012	0.620	.074	0.000	0.074	0.031	0.035	0.001	0.067	0.026	0.034	0.001	0.061	0.052	0.008	0.016	0.076
.006	.019	.783	.096	.000	.096	.005	.092	.000	.097	.010	.081	.000	.091	.021	.074	.001	.096
.01	.026	.915	.124	.001	.125	.021	.105	.001	.127	.021	.110	.001	.132	.073	.054	.003	.130
.02	.042	1.162	.185	.001	.186	.026	.163	.001	.190	.083	.097	.004	.184	.094	.082	.005	.181
.03	.054	1.319	.233	.001	.234	.083	.148	.004	.235	.156	.049	.035	.240	.125	.070	.017	.212
.04	.066	1.459	.268	.002	.270	.156	.107	.012	.275	.146	.092	.017	.255	.166	.013	--	1.173
.05	.076	1.563	.296	.003	.299	.146	.131	.013	.290	.166	.099	.023	.288	.146	.117	.016	.279
.06	.086	1.664	.318	.003	.321	.166	.151	.014	.331	.146	.152	.014	.312	.146	.125	.021	.292
.08	.105	1.839	.364	.004	.368	.104	.263	.008	.375	.125	.208	.013	.346	.146	.194	.015	.355
.10	.121	1.973	.408	.005	.413	.083	.323	.009	.415	.038	.355	.007	.400	.125	.249	.014	.388

[1] $d_c = \sqrt[3]{\frac{Q^2}{gb^2}}$ b = 0.42 foot. [2] $v_c = \sqrt{gd_c}$. [3] H = Z + d + Hv.

caused by increased velocity. Thus, sediment on the floor of the flume channel had far less effect on measured stage than either the changes in depth of flow or velocity would indicate.

For example, a 0.6-foot HS flume with a flow rate of 0.10 c.f.s. has a depth of flow of 0.408 foot and a velocity head of 0.005 foot for a total specific energy of 0.413 foot with clear water (table 3). Since there is no sediment on the floor of the flume, total energy equals specific energy in this case. With 1-percent soil in the measured water and stable floor sediment conditions, the depth of flow has been reduced 0.085 foot; but, at the same time, the stage of the water now includes 0.083 foot because of the depth of sedimentation, and the velocity head is increased 0.004 foot. Thus, the 1-percent soil in the water caused only an 0.002-foot decrease in measured stage, but a .002 increase in total energy. In most cases, there were decreases in stage when there was 1-percent sediment in the measured water, even though there were increases in the total energy.

The actual depth of flow with clear water is about three times the critical depth, while the actual velocity is about one-fourth the critical velocity so that the depth is measured well within the subcritical range. As the amount of sediment increases, both the depth and velocity of the measured water approach critical values.

USE OF RESULTS

Errors up to 30 percent are possible when you measure sediment-laden water with 0.6-foot HS flumes by using the standard calibration values. These errors can be reduced considerably, if corrections are made for stage-depth differences for the average flow rate and sediment in the water expected.

As an example, the following data were obtained during erosion studies conducted by using simulated rainfall. An 0.6-foot HS flume equipped with a Belfort water-stage recorder was used to record a hydrograph of the runoff from a 75-foot-long corn plot on an 8-percent slope. A motor-driven modified, Coshocton-type sample wheel was also used to obtain periodic gravimetric samples of the runoff. The silt load in the runoff water ranged from 2.0 to 4.17 percent by weight. Runoff rates and totals were determined both before and after making stage height corrections from table 1 based on silt load (table 4). For comparison, flow rates and total flows as determined from the gravimetric samples were also calculated. The total flow based on the corrections corresponds closely to the total flow based on the volume measurements and exceeds the total flow based on the calibration curve by 17.2 percent.

The calibration tests were all made starting with a flume clear of sediment and with a constant rate of water flow and percent sediment in the water during the test period. However, when making field measurements, the flow rates and the sediment loads usually range over rather wide values. If a flume becomes filled with sediment during a period of high flow rate, high sediment load, or both, it may take a long time, if ever, to reach an equilibrium sedimentation condition with a lower rate of flow, lower sediment load, or both, without mechanical cleaning.

Table 4.--Comparison of total flow determined by standard calibration factors, corrected factors based on experimental tests, and gravimetric measurements

Time, min.	H	Q-standard calibration	Silt content	Stage height correction[2]	Corrected	Q from[3] gravimetmic sample
	Ft.	C.f.s.	Percent	Ft.	C.f.s.	C.f.s.
0	0	0	2.00	0	0	0
3	0.215	0.0240	4.09	+0.019	0.0285	0.0319
6	.248	.0326	3.67	+.024	.0390	.0371
0	.240	.0302	3.52	+.022	.0362	.0393
12	.245	.0317	3.47	+.022	.0380	.0392
15	.243	.0211	3.84	+.026	.0384	.0469
18	.246	.0319	3.29	+.020	.0375	.0375
21	.248	.0326	3.46	+.022	.0390	.0403
24	.248	.0326	3.51	+.022	.0390	.0398
27	.246	.0319	3.44	+.022	.0382	.0385
30	.250	.0330	3.57	+.023	.0396	.0385
33	.251	.0334	3.68	+.024	.0405	.0417
36	.249	.0328	4.17	+.029	.0415	.0370
39	.247	.0323	3.63	+.024	.0392	.0384
42	.253	.0340	3.55	+.022	.0405	.0382
45	.247	.0323	3.66	+.024	.0392	.0402
48	.250	.0330	3.65	+.024	.0400	.0392
51	.246	.0319	3.88	+.028	.0400	.0454
54	.262	.0365	3.85	+.028	.0455	.0389
57	.247	.0323	3.68	+.024	.0392	.0395
60	.247	.0323	2.23	+.018	.0370	.0132

Total flow, cu. ft. 11.56.............. 13.69....13.97
Error, percent......17.2..................2.0

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[1] Holtan, H.N., Minshall, N.E., and Harrold, L.L. Field Manual for Research in Agricultural Hydrology. U.S. Dept. of Agr. Handb. 224, 215 pp. 1962. (Calibration values for flume used were almost same as in table.)

[2] From table 1 based on a 3-percent silt load.

[3] Converted to c.f.s. for purposes of comparison.

During the tests, care was taken to maintain free flow of water between the flume and the stilling well. During long periods of operation, sufficient sediment can get into the stilling well to prevent free operation of the recorder float. Frequent inspection and maintenance are usually necessary to insure reasonably accurate measurement of sediment-laden water with a HS-type flume.

SUMMARY

Calibration tests of a standard 0.6-foot HS flume were made using both clear water and sediment-laden water. Corrections to a standard calibration were determined for 1-, 2-, 4-, 6-, 8-, and 12-percent sediment in the measured water and flow rates from 0.003 to 0.10 c.f.s. Soil was used as the sediment in the first series of tests and sand was used for a second series.

The sediment-laden water caused measurement errors up to 30 percent when a standard calibration curve was used with a 0.6-foot HS flume. Differences in stage height caused by sediment in the measured water were largely caused by changes in the slope and the elevation of the floor of the flume and approach channel. Errors because of changes in viscosity and density of the measured water caused by suspended sediment were negligible.

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